PRINCIPLES OF RISK ASSESSMENT APPLIED TO MITIGATION OF PROGRESSIVE COLLAPSE

Bruce R. Ellingwood, Ph.D., P.E.
School of Civil and Environmental Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0355

Progressive collapse

A collapse that is triggered by localized damage that cannot be contained and leads to a chain reaction of failures resulting in a partial or total structural collapse, where the final damage is disproportionate to the local damage from the initiating event.

Events outside the design envelope

- Abnormal/accidental loads
- Design/construction error
- Occupant misuse

Significant progressive collapses

- Ronan Point, London, UK -1968
- Bailey's Crossroads, VA - 1973
- US Marine Barracks, Beirut, Lebanon – 1983
- L'Ambiance Plaza Apartments, CT - 1987
- Murrah Federal Building, Oklahoma – 1995
- Khobar Towers, Dhahran, Saudi Arabia - 1996
- US Embassies - Nairobi, Kenya and Dar es Salaam, Tanzania – 1998

Motivation

Is there a need for improved design practices?

- New building systems
- Demands for design beyond building code minimums
- Perception of increasing risk for certain facilities
- Public awareness of building performance and demands for safety

Best practices for reducing the potential for progressive collapse in buildings

Chapter 2: Acceptable risk bases

References appear in Chapter 7

Learning objectives

- To understand the importance of uncertainty and risk in engineering decision; and
- To present a framework for addressing low-probability/high-consequence events in structural engineering.

Current code provisions addressing progressive collapse in the US, Canada and Europe

- Performance requirement
- Minimum requirements for connectivity
- Damage tolerance - notional element removal
- Normative abnormal load (pressure or force)

ASCE STANDARD 7-05
General structural integrity

1. **General: §1.4** "Buildings and other structures shall be designed to sustain local damage with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage…"

2. **Combinations of Loads: § 2.5** "…strength and stability shall be checked to ensure that structures are capable of withstanding the effects of extraordinary (i.e., low-probability) events…"

Design requirements for progressive collapse resistance of federal buildings

- DOD Unified Facilities Criteria (UFC 4-023-03 Jan 2005)
  - Non threat-specific
  - Notional element removal
  - Net upward load on floor system: $1.0D + 0.5L$
  - Alternate path: $[(0.9D \text{ or } 1.2D) + 0.5L]^{*} + 0.2W$

- General Services Administration (June 2003)
  - Non threat-specific
  - Notional element removal
  - Alternate path: $[D + 0.25L]^{*}$

---

*For static analysis, the gravity portion of the load adjacent to and above removed element is multiplied by 2.

See also Appendix A

ICC Proposal S5

1605.1 General

- The building structure or portion thereof shall be constructed to the building will not suffer collapse as the result of an accident or incident to an extent disproportionate to the cause.

Class 3 buildings

- Shall be provided with horizontal ties, anchorage and vertical ties or shall be designed using alternate load path analysis

Class 4 Buildings

- Comply with all requirements for Class 3
- Perform systematic risk assessment taking into account all normal hazards that may be reasonably foreseen, together with any abnormal hazard

NATIONAL BUILDING CODE OF CANADA

§4.1.1.3(1) "Buildings... shall be designed to have sufficient structural capacity and **structural integrity**…"

Commentary C to Part 4

"**Structural integrity** is defined as the ability of the structure to absorb local failure without widespread collapse."

"Key components which can be severely damaged by an accident with a significant probability of occurrence (approximately **10^{-4}/yr** or more) should be identified, and measures taken to ensure adequate structural safety."

BUILDING REGULATIONS – UK

- "…in the event of an accident, the building shall not suffer collapse to an extent disproportionate to cause…"
- Scope: by occupancy class - generally, buildings 5 stories and higher
- Approaches
  - Minimum tie forces [e.g., principal structural elements in steel frames shall be capable of resisting tensile forces of 75 kN (17 k)]
  - Damage from notional removal of element limited to 15% of story area or 100 m^2
  - Key elements designed for 34 kPa (5 psi) (BS 6399 on Loads)

EUROCODE 1: General design and structural load requirements
(EN 1990; EN 1991-1-7)

Section 2: "A structure shall be designed in such a way that it will not be damaged by events like fire, explosions, impact or consequences of human errors, to an extent disproportionate to the original cause"

$$D + \mathbf{A_k} + \psi_1 Q_1 + \Sigma \psi_2 Q_i$$

ψ_1 and ψ_2 are tabulated for different loads

$$D + A_k + 0.5L$$
$$D + A_k + 0.3L + 0.2S$$
$$D + A_k + 0.3L + 0.5W$$

Performance-based engineering
Concept

An engineering approach that is based on

- Specific performance objectives and safety goals
- Probabilistic or deterministic evaluation of hazards
- Quantitative evaluation of design alternatives against performance objectives

but does not prescribe a specific technical solution

ICC Performance Code (2003)

Objective: To provide a desired level of structural performance….

Requirements:

Structures shall remain stable and not collapse…

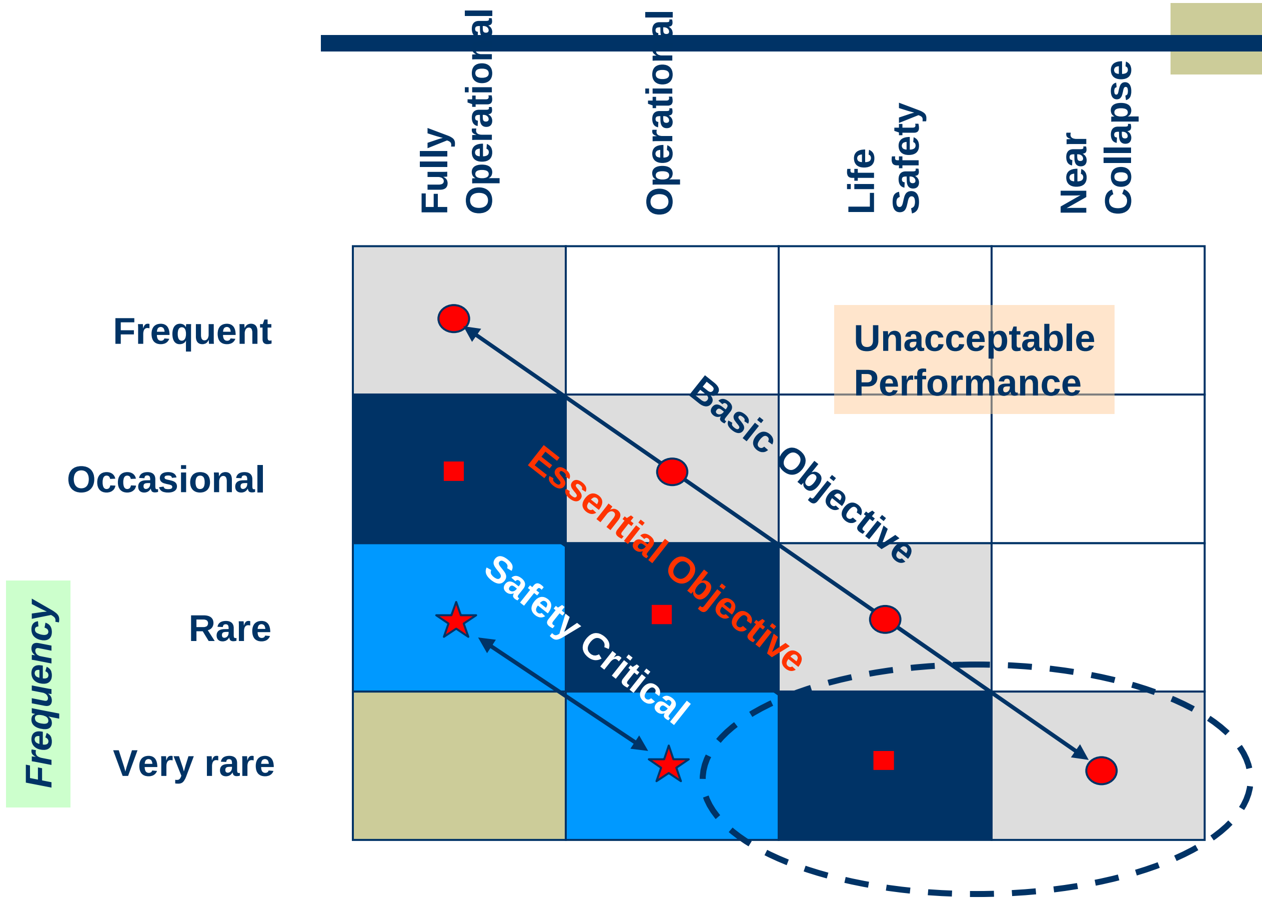
Structures shall be designed to sustain local damage…

Structures…shall have low probability of causing loss of amenity…

Design shall consider…effects of **uncertainties**…

Performance objective

SEAOC Vision 2000



Improving progressive collapse-resistant practices

- Risk assessment and probabilistic formulation of structural criteria
- Characterization of abnormal loads
- Strategies for mitigation
- Implementation in professional practice

Ingredients of risk

- Probability of occurrence
  - Hazard
  - System response, damage states
- Consequences
  - Deaths
  - Dollars
  - Downtime
- Context – who is the decision-maker?

Why base engineering decision on formal risk assessment?

- Experience is insufficient to define risks due to low-probability, high/consequence events
- Achieve performance consistent with expectations and resources
- Target investments to achieve maximum benefits in risk reduction
- Maintain transparency in decision process

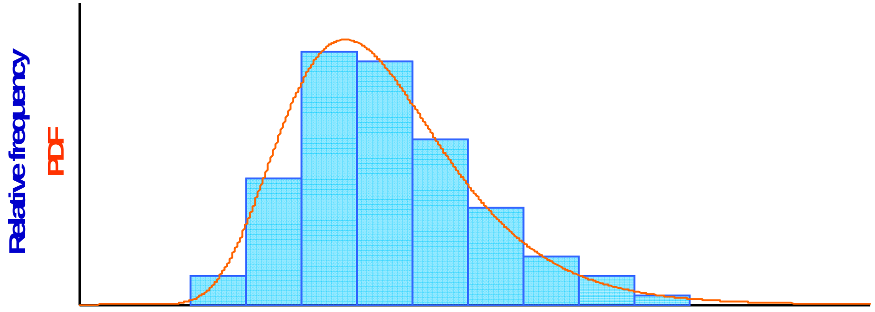
DOE-STD-1020-02

Natural phenomena hazards design and evaluation criteria

Cat.	Performance goal	Hazard (/yr)	Failure prob.(/yr)
1	Occupant safety	2×10^{-3}	1×10^{-3}
2	Occupant safety, cont'd function	1×10^{-3}	5×10^{-4}
3	Occupant safety, cont'd function; hazard confinement	5×10^{-4}	1×10^{-4}
4	Occupant safety; cont'd function; high confidence of hazard confinement	1×10^{-4}	1×10^{-5}

Probabilistic models of uncertainty

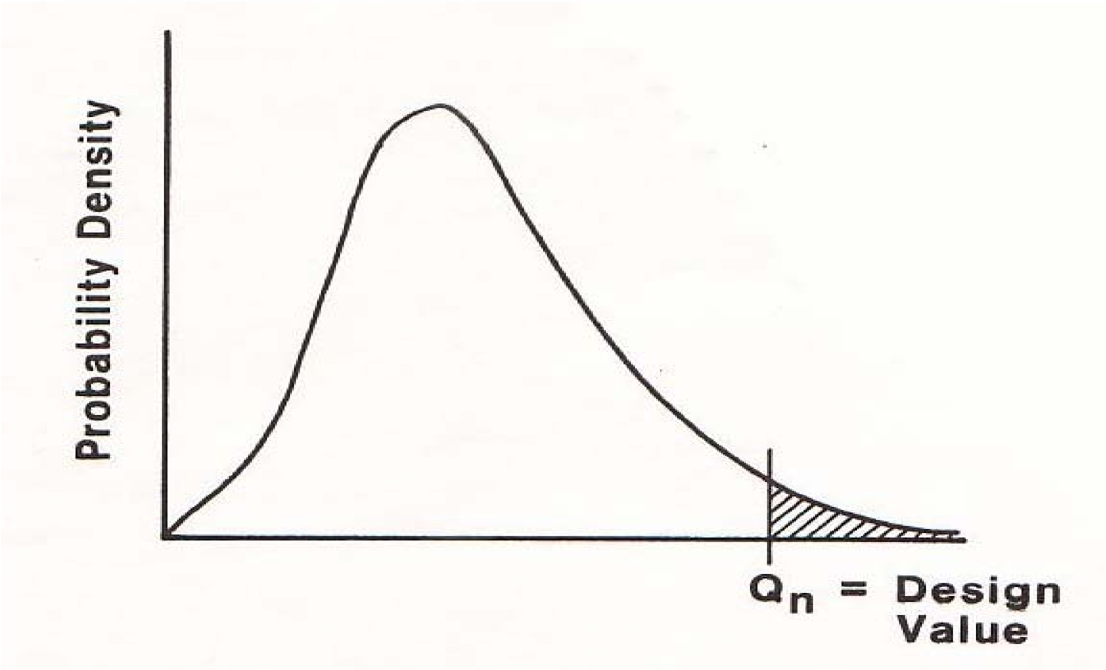
- Random variable: A variable that can assume any of a range of values, the precise value being uncertain.



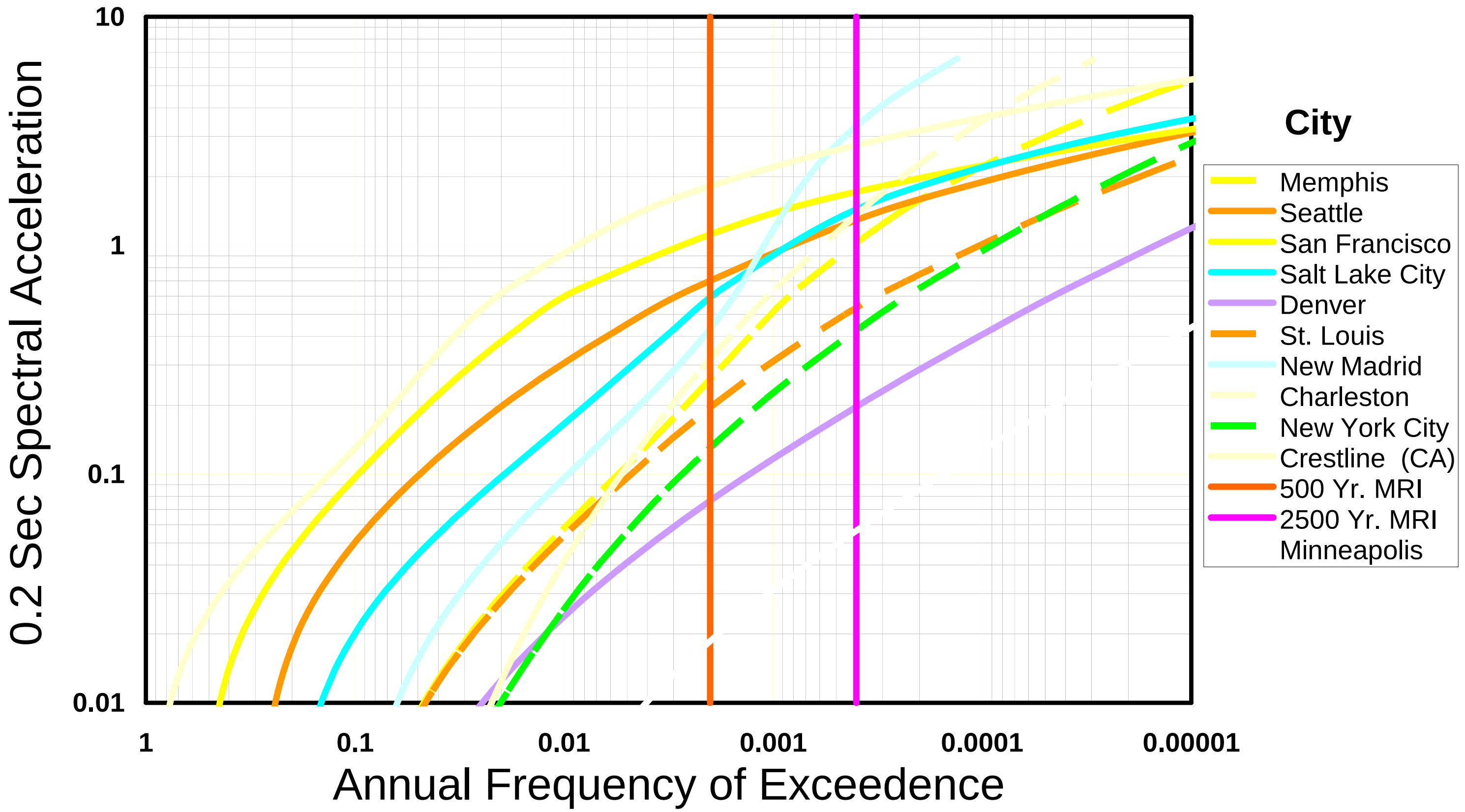
- Probability laws describe relative frequency of occurrence (statistical regularity).

Probabilistic load models

Design loads for ASCE Standard 7-05



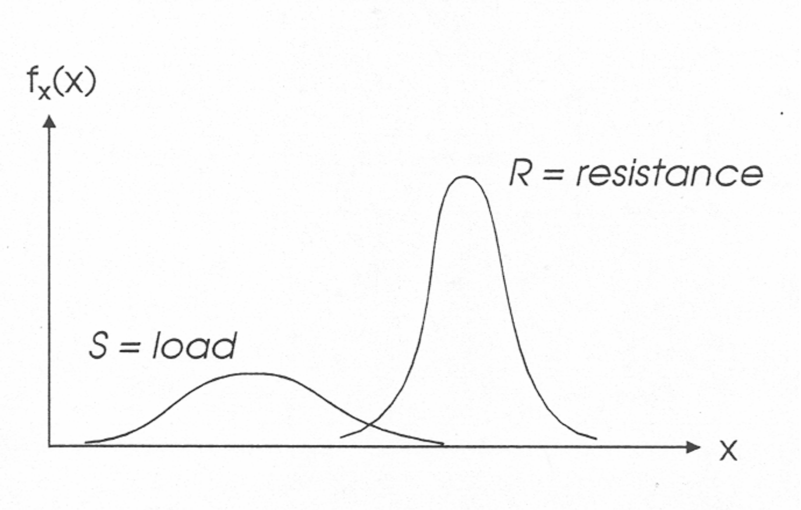
Seismic hazard curves



Limit state probability

R, S are random variables describing capacity and demand

LS: R < S

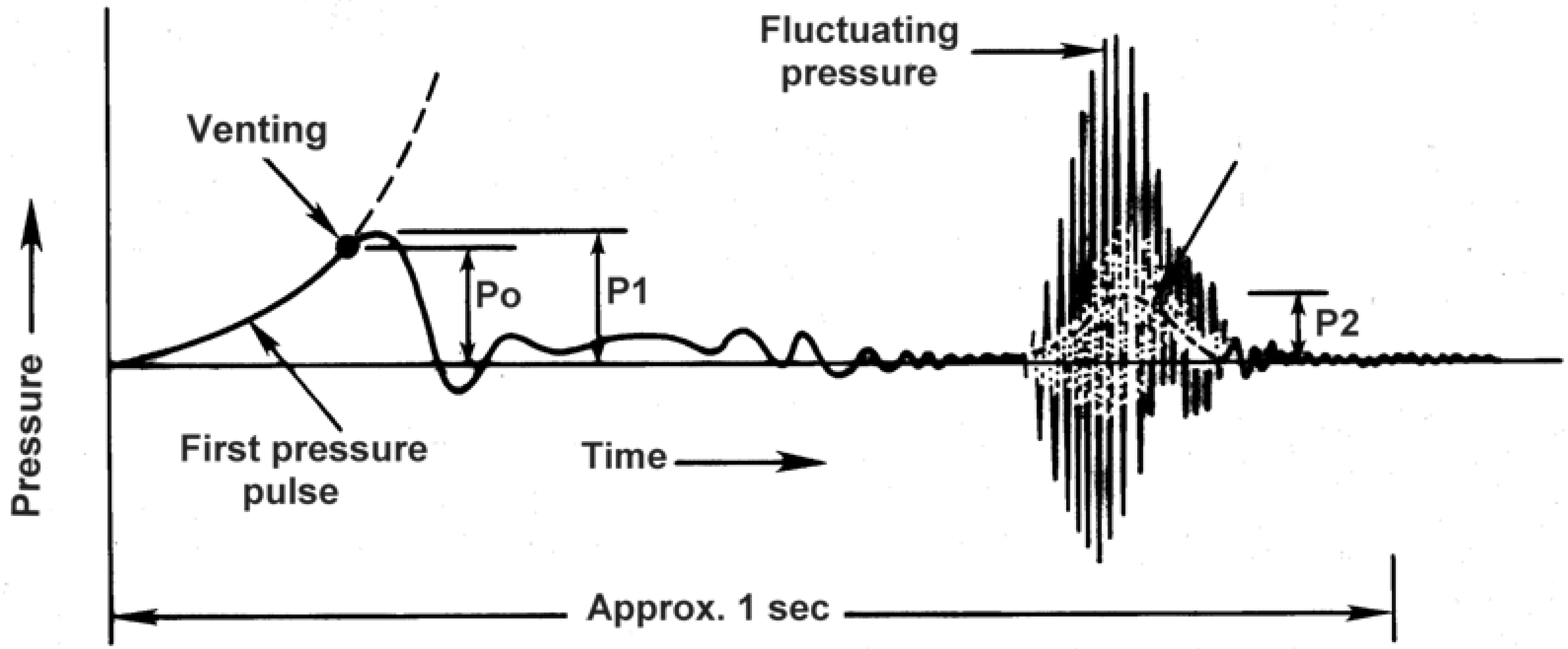


$$P[LS] = P_{LS} = P[R < S]$$

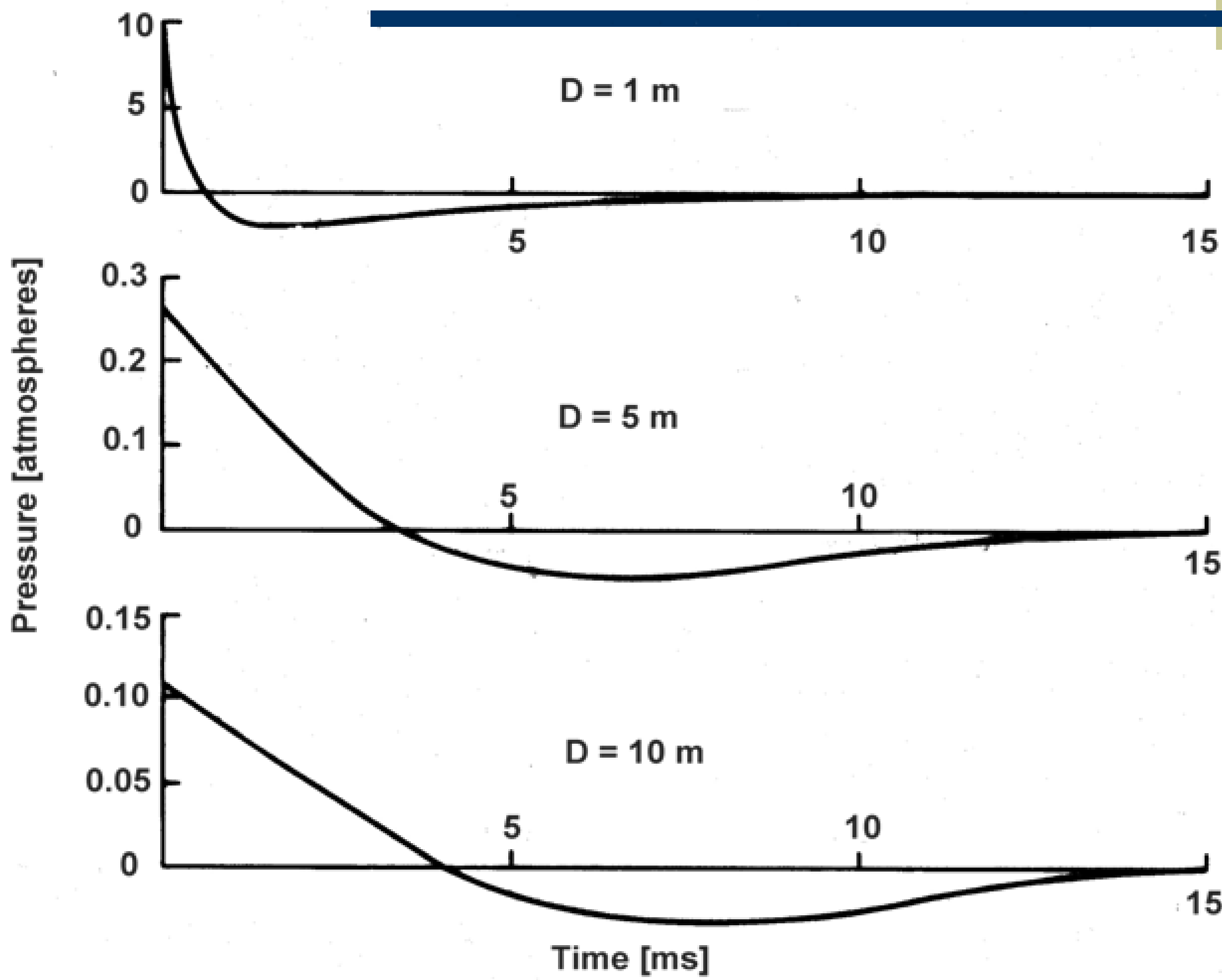
Sources of abnormal loads

- Aircraft impact
- Bomb explosion
- Design/construction error
- Fire
- Gas explosion
- Occupant misuse
- Transportation, storage of hazardous materials
- Vehicular collision

Explosion of natural gas in residential compartments

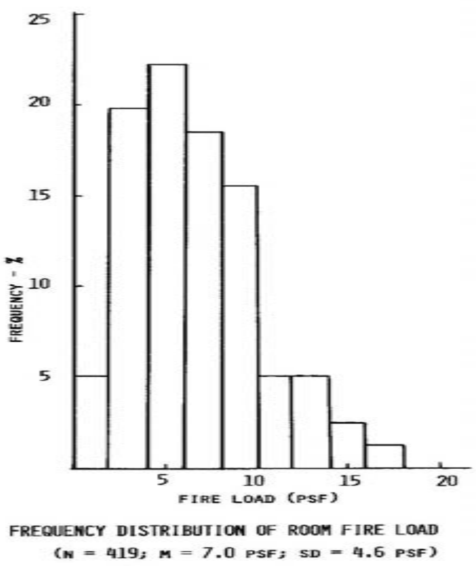


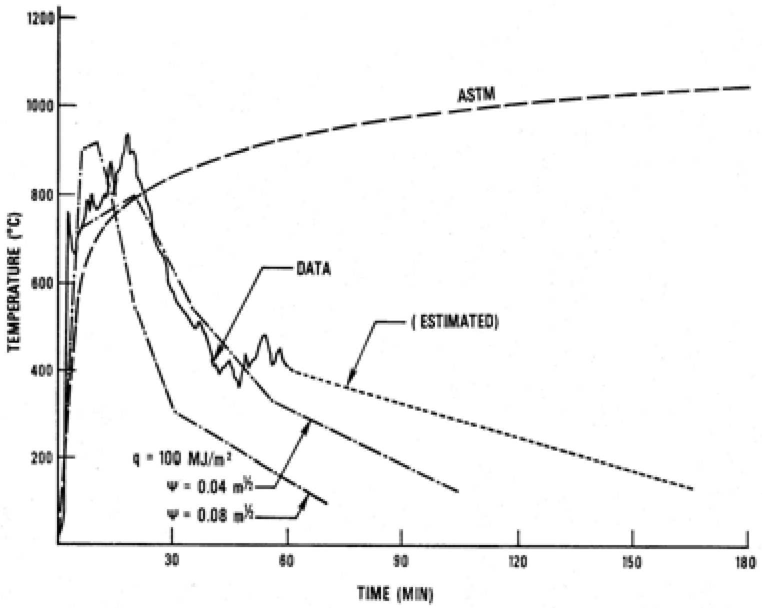
Detonation of explosives



Structural actions due to fire

General and clerical offices





Incidence of abnormal loads

- Gas explosions (per dwelling): 2×10^{-5}/yr
- Bomb explosions (per dwelling): 2×10^{-6}/yr
- Vehicular collisions (per building): 6×10^{-4}/yr
- Fully developed fires (per building): $5 \times 10^{-8}/m^2$/yr

Measuring risk of progressive collapse

(Deconstruction of risk)

$$\lambda_{Collapse} = \Sigma_H \Sigma_D \, P(Collapse|D)\, P(D|H)\, \lambda_H$$

- λ_H = mean rate of hazard/yr
- $P(D|H)$ = probability of structural damage, given hazard
- $P(Collapse|D)$ = probability of collapse, given damage

$\lambda_{Collapse} < 10^{-6}$/yr

Measuring risk of progressive collapse

(Scenario analysis)

$$P(\text{Collapse}|\text{Scenario}) = \Sigma_D P(\text{Collapse}|D)\, P(D|\text{Scenario})$$

- P(D|Scenario) = probability of structural damage, given a postulated scenario
- P(Collapse|D) = probability of collapse, given damage
- P(Scenario) = ???

Abnormal loads and progressive collapse

Strategies for risk mitigation

$$\lambda_{Collapse} = P(Collapse|D)\ P(D|H)\ \lambda_H$$

- Control occurrence of hazard
- Design structural elements to withstand load from hazard
- Design structural system to absorb local damage without collapse

Control hazard

$$\lambda_{Collapse} = P(Collapse|D)\, P(D|H)\, \lambda_H$$

- Limit access – stand-off distances
- Provide protective barriers, shields
- Install annunciators
- Install active control systems
- Minimize fuel loads
- Proscribe hazardous materials

Design key structural elements

$$\lambda_{Collapse} = P(Collapse|D)\ P(D|H)\ \lambda_H$$

- Normative abnormal loads to prevent failures of essential structural elements
- Permit development of alternate paths

Design system to absorb damage

$$\lambda_{Collapse} \approx P(Collapse|H)\ \lambda_H$$

- Redundancy/overall stability
- Connectivity
- Ductility
- Shear strength
- Capability to withstand load reversals
- Compartmentation

Code implementation

- General design principles
- Specific design requirements

General design principles

- Performance objective
  - Life safety
  - Economic losses
- Guidelines to when *specific* progressive collapse provisions should be considered?
- Load combinations
- Structural system stability

Risk mitigation by building occupancy

"Moderate risk"

Building type and occupancy	Risk mitigation options
Low to high-rise buildings Moderate to high density occupancies. Public assembly occupancies Certain governmental, financial institutions Buildings vulnerable to a known hazard Incidence 10^{-5} to 10^{-4}/yr ASCE 7-05 Category II, III, IV	Design for ductility, energy absorption/dissipation, enhanced joint or connection detailing. Evaluation of structural vulnerability. Evaluation of vertical/horizontal structural discontinuities. Enhanced structural stability measures.

Risk mitigation by building occupancy

"Substantial risk"

Building type and occupancy	Risk mitigation options
Low to high-rise buildings Moderate to high-density occupancies Key governmental, international institutions Monumental or iconic buildings Critical or essential facilities Incidence rate 10^{-4}/yr or greater ASCE 7-05 Category II, III, IV	Threat and probabilistic risk assessment Engineer structural systems to develop alternate load paths Engineer key elements to preserve system stability Architectural features to allow rapid evacuation and access to first responders. Peer review of design concept

Design criteria for low-probability/high-consequence events

Wind vs Fire

Wind load (W)

- $\lambda_{Collapse} = P(Collapse|D)\ P(D|W)\ \lambda_W$
- $\lambda_W = 1/yr$
- $P(D|W) \approx 10^{-5}/yr \quad \rightarrow \quad \mathbf{1.2D + 1.6W + 0.5L}$
- $P(Collapse|D) < 0.10$

Fire (A_F)

- $\lambda_{Collapse} = P(Collapse|D)\ P(D|F)\ \lambda_F$
- $\lambda_F \approx 1 \times 10^{-4}/yr$ (5,000 m^2 floor area)
- $P(Collapse|F) \approx 0.01 \quad \rightarrow \quad \mathbf{1.2D + A_F + 0.5L}$

ASCE Standard 7-05

General structural integrity

§1.4 "Buildings and other structures shall be designed to sustain local damage with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage…"

§2.5 "…strength and stability shall be checked to ensure that structures are capable of withstanding the effects of extraordinary (i.e., low-probability) events…"

§C2.5 Load combinations for extraordinary events

$$(0.9 \text{ or } 1.2)\ D + (0.5L \text{ or } 0.2S) + 0.2W^*$$

$$(0.9 \text{ or } 1.2)\ D + \mathbf{A_k} + (0.5L \text{ or } 0.2S \text{ or } 0.2W^*)$$

---

*In lieu of 0.2W, impose lateral notional force $H = 0.002\ \Sigma P$ at each floor

AISC 2005 Specification for Structural Steel Buildings

Appendix 4: Structural design for fire conditions

- Performance objective:

  "Structural components, members and frames shall be designed so as to maintain their load-bearing function throughout the design-basis fire and to satisfy other performance requirements stipulated for the building occupancy."

- Load combinations:

  Gravity: $(0.9 \text{ or } 1.2)D + \mathbf{T} + 0.5L + 0.2S$

- Stability: Lateral force = $0.002\Sigma P$ at each floor

Specification of design strength

Limit states design (LRFD)

Design strength = φR_n

- R_n = nominal strength (mean strength)
- φ = resistance factor

Specific design requirements

- Detailing for continuity and ductility (e.g., ACI 318-02 § § 7.1, 13.3.8, 16.5, 21)
- Consideration and provision of alternate load paths
- Provision for structural element resistance to specified abnormal loads (key element design)

Illustration of risk assessment

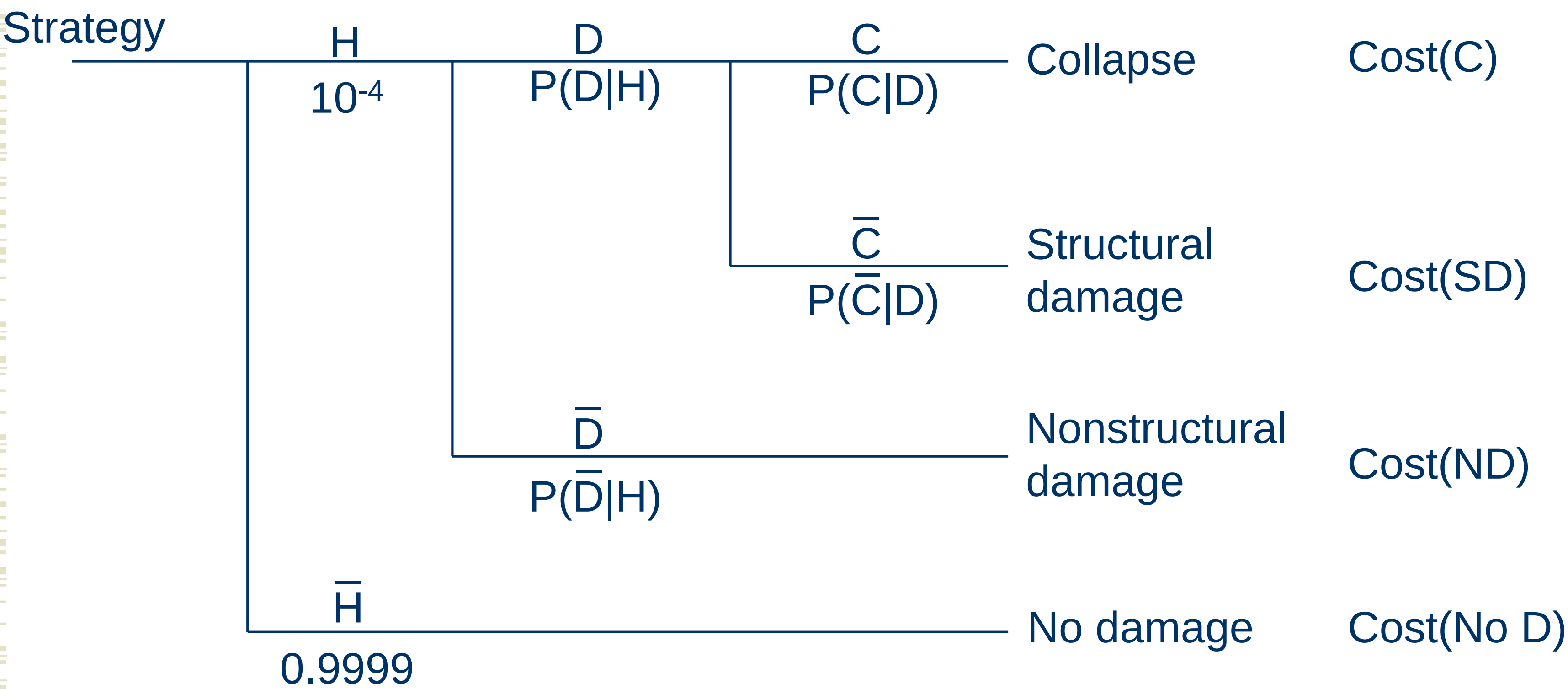
- Expected cost is determined from:

$$\text{Cost} = \text{Cost}_{des} + \Sigma\, \Sigma\, \text{Cost}(DS_i)\, P[DS_i|D_j]P[D_j|H]\, \lambda_H$$

- DS_i is outcome (local damage, partial collapse, etc)
- Each design alternative has an expected cost.

Illustration of risk assessment

$$\text{Cost} = C_{des} + \Sigma_i\, C(DS_i)\, P(DS_i)$$



Progressive collapse risk mitigation issues

- Understanding the nature of the hazard
- Selection of performance goals
- Hazard-specific vs non hazard-specific design approaches
- Scenarios, uncertainties and risk analysis
- Continuity, robustness, compartmentation, key element design
- Value engineering; investment in risk reduction
- Professional liability and contractual requirements